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An Alternative Version of a Liquid Scintillator Detector: Totally Active Configuration

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ABSTRACT

I suggest an alternative design for the NuMI off axis detector based on segmented liquid scintillator with minimum amount of passive material, “a poor man’s liquid argon detector”. A specific design is suggested as a convenient means of studying physics performance, cost, and construction issues. The first look suggests that the cost for such a detector, with a fiducial mass about half of the baseline detector, would be very comparable to the current baseline detector. I urge more intensive and broader investigation of this option since such a configuration might provide a significantly higher efficiency for ν_e detection with lower background.

Introduction

The liquid scintillator technology is the current baseline option for the proposed NuMI offaxis experiment. It is the purpose of this note to suggest a somewhat different version of a detector based on this technology, more specifically a totally (almost) active version. This could be viewed as one additional, and extreme point, in the optimization process where the key parameter is the ratio of inert material, particle board, to the active medium, namely liquid scintillator. In the current version, this ratio (in mass) is about 6; the version discussed here takes it all the way down to almost zero.

The motivation for this extreme point of view is that such a detector, characterized by continuous sampling and totally active volume, would provide better energy resolution and much better discrimination between ν_e interactions and background events. These factors could more than offset the smaller mass of this configuration resulting in larger value of FOM plus smaller dependence on how well one can extrapolate backgrounds from the Near to the Far Detector.

One might view such a detector as a poor man’s liquid argon detector. There the granularity is given by the wire spacing for two of the coordinates and timing resolution for the third. The wire spacing in ICARUS is 3mm but larger pitch up to 6mm is discussed for the much larger next generation detectors. The wires are crossed at 60^{o} and for some configurations one of the planes is not used or unavailable. The radiation length in liquid argon is 14 cm, a factor of about 3.5 shorter than in mineral oil. Thus the granularity of our detector, if expressed in terms of radiations lengths, might well be within a factor of two of what is contemplated for liquid argon.

I am suggesting two additional philosophical modifications which appear more natural and more advantageous for the approach discussed in this note. The first one is the use of readout at only one side of the detector – this would allow more flexibility in filling and draining and also expose the most vulnerable ends, namely the places where there is a glue seal. The second one, made attractive by the high density of readout ends, is to put the APD's, associated electronics, cooling and readout from several modules into a single box. None of these two features are an essential part of this version but my gut feeling is that they will simplify construction and assembly and probably also reduce the overall cost.

A straw man (or woman) design

I describe here one set of parameters which, on the first glance, appear to be an appropriate starting point for optimization. I want to emphasize that no quantitative optimization has been performed to date.

The design is at least partly driven by a feature unique to this design which may not be obvious on the first glance, ie that the size of a cell in the longitudinal (beam) direction can be made as large as physics, light collection and mechanical support issues dictate, without any price penalty. Quite the contrary, the cost goes down with larger size since the number of fibers, APD's. electronics and manifolds decreases as that dimension increases. I feel that this may well be an area where significant optimization would be useful and could well improve this initial "design".

Regarding the readout and electronics, my vision here is that 10 neighboring modules with the same orientation – 2 transversely and 5 longitudinally) - would go into the same electronics box. The two modules in the same plane feeding the same box would have the fiber collection ends of their manifolds next to each other, ie each alternate module would be effectively rotated by 180^o around a vertical axis, giving alternating righthanded and lefthanded modules. In this suggested arrangement the fiber "pigtails" required would not need to be longer than 50cm or so.

I describe next the parameters for this design, and where appropriate give some justification for the numbers chosen:

Basic cell area (inside dimensions): 3.8 cm (transverse) x 4.5 cm (beam direction)
Basic module: 32 cells, 17.5 m long, 125 cm wide; I assume 2 mm wall size for the exterior walls to provide additional strength. 1 mm for the interior cell dividers. I also assume that since we increase the thickness of the cell in beam direction (4.5 cm rather that 2.6 cm in baseline design) we can increase the length of the module to 17.5 m without an intolerable light output loss. This conjecture has been verified at some level by simulations mentioned below.
Single plane: 17.5 x 17.5 m in cross section, containing 14 modules
Total detector: 2000 planes, with alternating vertical and horizontal orientation of the modules, overall dimension of 17.5 x 17.5 x 98 m (assuming no gaps between planes and modules).

These parameters translate into the following totals:
448 cells/plane
2.8 x 10^4 modules, each module weighing 150 kg empty and containing 823 kg of -- scintillator when filled
2.8 x 10^4 APD units (32 channels each)

2.8×10^3 electronics boxes
8.96×10^5 total cells
3.32×10^4 km of fiber (assuming 37 m /cell)
Mass of the detector – 27.3 kt, of which 23.1 is the active mass, ie scintillator

<u>Possible construction</u>

This is very preliminary and very likely will be altered significantly once the *cognoscenti* (aka engineers) have a go at it. But I am putting it forwards as a feeble existence proof to show that it may be feasible without significant physics or price penalties. The preliminary engineering investigations have not uncovered any fundamental problems with the basic design being suggested here. There is some question regarding the potential complications introduced in transportation of longer modules suggested here but it is unlikely that this is a show stopper; furthermore 17.5 m suggested module length is not a crucial feature of this option.

The basic idea is that one erects strong I-beams on each side of the detector (*a la MINOS*), 18+ meters high which serve as support for longitudinal beams. These longitudinal beams then serve as support structure for access to the top of the detector, for platforms for the readout boxes. and for any hardware required for filling. The vertical beams on the readout side can also provide support for readout boxes for horizontal modules.

If overburden turns out to be necessary, this structure could be extended slightly upwards to provide a support for overburden material. To put the possible load in perspective, 3 mwe of material would give about 2 kt load in 30 m (approximate MINOS detector length), to be compared with 5.4 kt load in MINOS.

As far as the assembly of actual modules goes, one could visualize construction of a bookend initially and then attaching successive layers of modules to it and to preceding modules, for example by gluing. One might worry about hydrostatic pressure effects in this assembly. There are several obvious ways of alleviating it. One could make the exterior load bearing module walls thicker – I have already increased them to 2 mm from 1.5 mm in baseline design. One could also have a structure on the sides which provides shelves to support the ends of the horizontal modules. Finally, one could have periodic interruptions in the detector with additional structural beams in its main volume which would give any reqired support to the detector.

The vertical modules would ideally rest on a plate that has slots to allow access to potential drain holes and/or any other feature of the module for which the access would be either convenient or necessary.

<u>Physics Performance</u>

It is clear that the actual performance of such a detector, we call it Totally Active Scintillator Detector (TASD) for the purpose of this discussion, can be only understood properly with realistic simulations. But some obvious comments may already be made here.

<u>Fiducial volume</u>. I think we can approximate Peter Litchfield's fiducial volume acceptance algorithm used for analysis of the baseline detector by assuming that the unusable part of the detector consists of 75 cm of on each side and 4 m at the end. In that

approximation, the useful fiducial fraction for the baseline detector is 82.5% and 80.2% for TASD, giving fiducial masses of 41.25 kt and 21.9 kt respectively.

Light output. The cell thickness is taken to be 4.5 cm in TASD vs 2.6 cm in the baseline detector. In addition, the aspect ratio is somewhat better, ie almost square, in TASD. These two factors compensate very closely the additional loss of light from the far end of the detector in going from 14.6 to 17.5 m. Thus the light output for the worst case should be very similar for both designs. This been verified recently by means of a Monte Carlo simulation (NuMI-Offaxis Note-29) based on a modified version of a program written by Keith Ruddick some time ago. Furthermore, because of much higher density of measurements in TASD, loss of signals in individual cells due to inefficiency or noise should have much smaller impact on the results from the analysis algorithms.

Spatial granularity. The density of measurements here is somewhat more than a factor of 2 higher than in the double readout (x and y) RPC's and a factor of about 5 higher than in the baseline scintillator design. This should facilitate tracking and allow one to have higher efficiency both for low energy muons and soft gamma conversions. This latter feature should provide additional handles on identification of potential NC and CC backgrounds.

Energy measurement. About 85% of the detector mass is active. Thus energy resolution should be significantly better allowing better background discrimination by virtue of total visible energy cut. In addition, there are about 6 energy samplings in each view in the first radiation length. That should permit rejection of a significant fraction of gamma conversions based on their expected initial double-MIP pulse height. A good description of TASD is that it combines the best features of both RPC and liquid scintillator technologies and improves on the best feature of each one.

Cosmic ray background.This detector, being totally live would not require a veto shield. In addition, undetected muons penetrating to the inside of the detector and interacting there, would be strongly suppressed. Thus the probability that an overburden would be required is smaller here.

Detector Asymmetry. The liquid scintillator detectors of the nature proposed here are intrinsically asymmetric. TASD is both up/down and left/right asymmetric because of one-sided readout. This should not present a fundamental problem but the reconstruction and event identification algorithms might well have to take an account of it since the events on the readout side may well provide better discrimination.

Other physics topics. I believe that TASD has better physics capability in a number of additional areas, specifically those where the resolution and systematics are more dominant. The obvious examples are measurement of $\sin^2\theta_{23}$, precise measurement of Δm^2_{23} and search for small admixtures of sterile neutrinos.

Potential improvements. It is quite likely that the design outlined here can be significantly improved (as can probably be the baseline design) by additional optimization work. I want to mention here two possibilities:

1) One might use two thinner fibers. For example, two 0.5 mm fibers give the light output that is comparable or somewhat better than one 0.8 mm fiber (NuMI-Offaxis Note-29). The cost of the fibers, assuming that it scales with the fiber cross sectional area, would be about 22% lower. I doubt that the excess amount of labor would significantly reduce these savings. In addition, such 2 fiber configuration could be fitted into a square 1 mm on the side, as opposed to a 1.37

mm square for single 0.8 mm fiber configuration. Given that the active surface of each APD pixel is 1.6 mm square, this would allow significantly more relaxed tolerance on the precision of coupling.

2) Constraining the fibers to be closer to the center. This appears to yield about 10% more light. Again, the extra labor cost would have to be weighed against this potential gain.

Cost Comparison

We are rapidly approaching the situation where we shall be able to do reasonably reliable cost estimates between the different offaxis detector options. In the meanwhile, for the purpose of this note I have done a rough estimate of relative cost of TASD vs the baseline detector based on Gina Rameika's spreadsheet for the liquid scintillator making some crude assumptions where no reliable data are as yet available. I have not made any allowance for possible savings in TASD due to economies of scale which might be appreciable since the purchases from outside vendors will tend to be larger. Below I compare my estimates with the current baseline detector (liquid scintillator) figures.

Scintillator. Using the price of $1191/ton the total cost for TASD and baseline are **$27.48M** and **$8.47M** respectively.

Fiber. Using the price of $0.56/m the total costs are **$18.57M** and **$9.77M.**

Modules. Here the calculation needs to be more detailed to be precise. For now, I have kept the fixed one time costs the same, scaled the cost of the manifolds and end pieces by number of modules, assumed that half of the cost of an individual extrusion is in M&S (which we shall scale by relative mass of the extrusions used in each version) and the other half in labor (which is scaled by the total length of all extrusions required). Under these scaling assumptions, the two costs are **$12.99M** and **$6.79M.**

APD's. The price for a unit (32 channels) is quoted as $86. This yields the totals of **$2.41M** and **$1.71M.**

Rest of FEE and DAQ. Again, this has to be done in much more detail, especially since I am proposing a somewhat different design of front end boxes, which in TASD would accept output from 10 modules. For now, I scaled the cost of most of the components and board assembly ($1.187M) for the baseline detector by relative number of APD's and assumed the other costs to remain the same. This yields for the totals **$4.35M** and **$3.74M.**

Passive absorber. It is not needed for TASD so the two costs are **$0M** and **$13.15M.**

Shipping. The total costs for this item are as yet unavailable. Based on particle board shipping costs (first estimate of $3M), I estimate total shipping cost for the baseline detector to be about $5M. The TASD shipping should be cheaper, because total mass is less, there is only one kind of material being shipped, and shipping mineral oil should require less handling and hence be cheaper than shipping particle board. I assume cost savings of $2M, ie total costs of **$3M** and **$5M.**

Installation. This is a big ticket item for liquid scintillator baseline detector, current estimate being $10.04M. Without a specific model for installation of TASD I find it hard to guess whether there should be a significant cost variance and if so how much and in which direction. So for now I take the baseline figure of **$10.04M** as being appropriate for both detectors.

Project Management. Assuming that both designs will take about the same length of time to complete construction, this item should be very similar in the two cases. The TASD may be somewhat simpler because of no need for wood/extrusion module assembly and thus may require fewer managers. Nevertheless I accept **$3.58M** for each.

Veto Shield. It is being assumed that the baseline detector will require a veto shield. The TASD, being fully active, would not need it. The cost of veto shield for the baseline detector, including its installation has not been estimated yet. One can do crude scaling from the MINOS veto shield; the length of the baseline detector is about 5 times that of MINOS, the width of the required shield about 2.5 times larger. The MINOS shield cost was about $0.5 - $0.75M but the active material used and the electronics were significantly most expensive. The labor cost for the installation, however, may well scale as the area. Thus the cost here might be a factor of 5-10 higher. I will assume a cost for both M&S and SWF here of $3M giving **$0** and **$3M**.

Enclosure and its Outfitting. Again, this is a big ticket item and one needs to understand the potential differences. Since the volume of this detector is almost a factor of 3 smaller, I will assume that the cost for TASD will be 50% less. Taking recent numbers, I obtain **$13.5M** and **$27M.**

Support structure, plumbing, etc. Very little work has been done here so far and this is certainly a case where "the devil is in the details". The TASD costs may be lower here because of the shorter length and width of the detector and the fact that the plumbing for filling is only on one side. But the external supporting structure will be more complicated. Based partly on MINOS experience, I assume equal costs of **$5M,** fully realizing that this number can be off considerably.

Near Detector. The costs here should be comparable; the baseline detector cost may be slightly higher if one goes to a multi-layer version of it, which certainly would not be necessary for a TASD version. Based on the current MINERνA estimates, I will take the cost to be **$2M** for each.

Summary. The total costs for the two detectors turn out amazingly to be almost identical: **$103.28M** and **$101.25M** for TASD and baseline detectors respectively. These are raw costs, not containing any burdens. Given the crudeness of some of these estimates my conclusion is that to the accuracy of 15-20% one can build a TASD of half the fiducial mass of the baseline detector for the same price. One should be able to check and improve on these numbers significantly in the near future based on Gina's work currently in progress.

There is one important additional point to be made here. About 45% of the TASD cost comes from the purchase of two items – liquid scintillator (lumping together, maybe unfairly, the mineral oil and the fluors) and green fibers. I feel that once one does a fair allocation of all the burdens, allowing for their variation from item to item to reflect varying amount of EDIA required, different appropriate overhead and different risk factors (ie necessary contingency), this will result in an additional significant relative cost reduction for TASD.

Conclusions.

A totally active liquid scintillator detector appears, on the first glance, to be quite an attractive option for the NuMI offaxis detector. Much additional work needs to be done to understand the pros and cons of this option and how it compares with the current baseline detector in cost. in performance and in the complexities of construction. <u>I would like to cojecture that it is highly likely that the gain in efficiency and reduction of background made possible by the totally active volume will give a significantly higher FOM for this option even with only</u> <u>half the fiducial mass</u>. Thus a broader effort to pursue this possibility appears highly advisable. Some of the most important first tasks are:

a) understanding of all the structural issues
b) performing realistic simulations and developing optimized reconstruction algorithms to understand the physics capability
c) a professional cost estimate based on a more detailed design
d) optimization of the parameters of the detector

<u>Acknowledgements.</u>

The details of this proposal, as well as the basic detection ideas, are based very much on the work done over the past few years by the liquid scintillator enthusiasts, especially the Minnesota group. The preliminary costs presented here have been made much easier by the costing work being done currently by Gina Rameika.